Barrier Bucket Studies in the Fermilab Recycler Ring

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20th ICFA Advanced Beam Dynamics Workshop

High Intensity High Brightness Hadron Beams

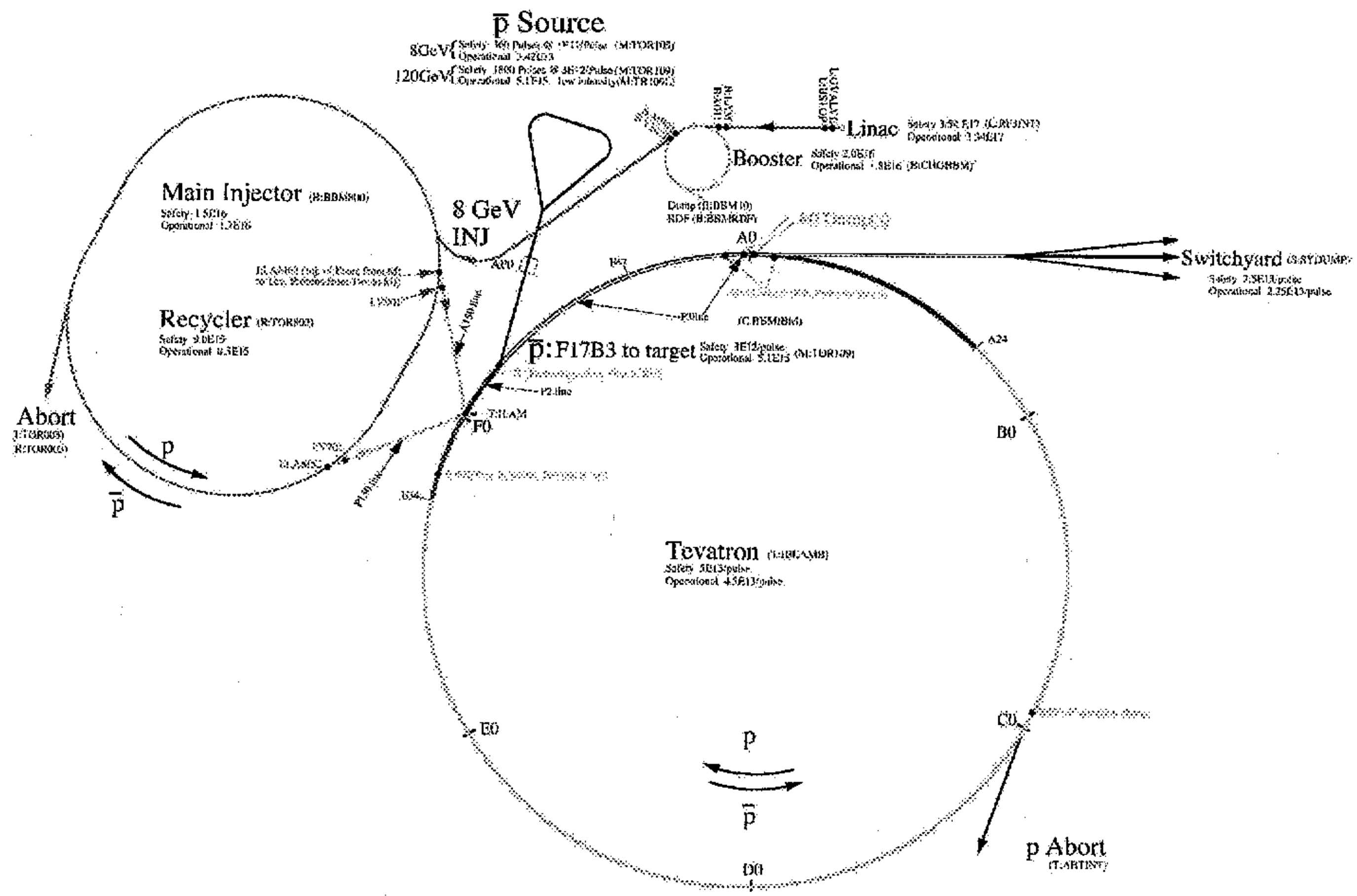
Fermilab

April 8 - 12, 2002

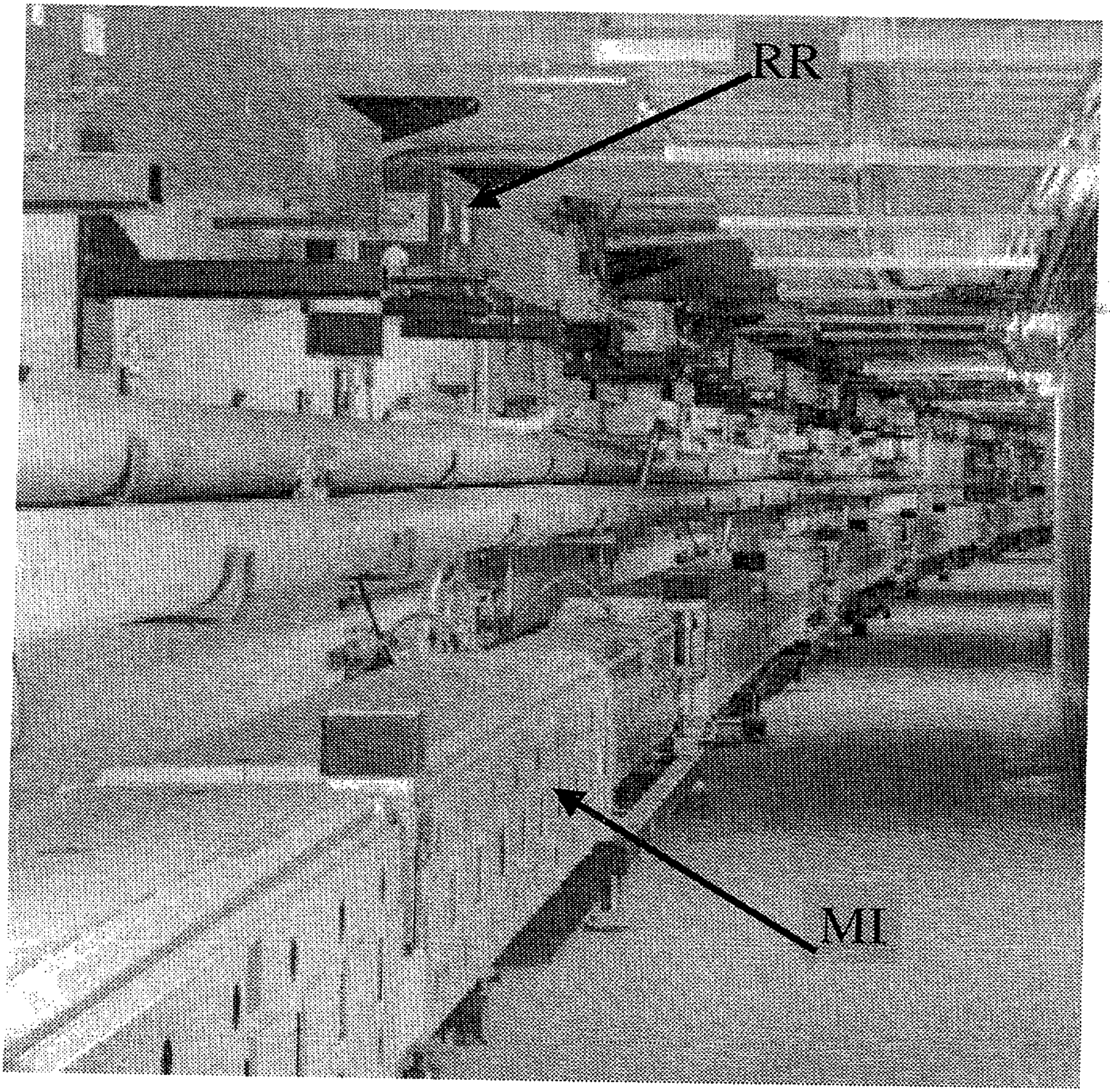
Outline

- Fermilab Recycler Ring (a pbar storage Ring) and its role in Collider Run II
- Barrier Buckets in RR
  - Selection of Wave forms for RR barrier buckets
  - Beam dynamics simulations and RF manipulations in RR
- Beam stacking and unstacking using barrier buckets in RR
- Conclusions and plans

Fermilab Site



Recycler Ring in MI Tunnel



RR Machine Parameters

Table 1.1: Recycler ring parameter list.

Circumference	3319.400	m
Momentum	8.889	GeV/c
Number of Antiprotons	2.5×10^{12}	
Maximum Beta Function	55	m
Maximum Dispersion Function	2.0	m
Horizontal Phase Advance per Cell	86.8	degrees
Vertical Phase Advance per Cell	79.3	degrees
Nominal Horizontal Tune	25.425	
Nominal Vertical Tune	24.415	
Nominal Horizontal Chromaticity	-2	
Nominal Vertical Chromaticity	-2	
Transition Gamma	20.7	
Transverse Admittance	40	π mmmr
Fractional Momentum Aperture	1%	
Superperiodicity	2	
Number of Straight Sections	8	
Number of Standard Cells in Straight Sections	18	
Number of Standard Cells in Arcs	54	
Number of Dispersion Suppression Cells	32	
Length of Standard Cells	34.576	m
Length of Dispersion Suppression Cells	25.933	m
Number of Gradient Magnets	108/108/128	
Magnetic Length of Gradient Magnets	4.267/4.267/2.845	m
Bend Field of Gradient Magnets	1.45/1.45/1.45	kG
Quadrupole Field of Gradient Magnets	3.6/-3.6/7.1	kG/m
Sextupole Field of Gradient Magnets	3.3/-5.9/0	kG/m^2
Number of Lattice Quadrupoles	72	
Magnetic Length of Quadrupoles	0.5	m
Strength of Quadrupoles	30	kG/m

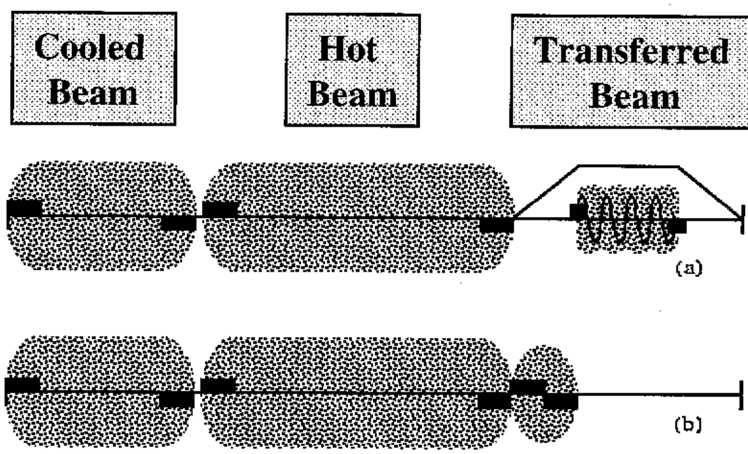
Run II parameters with RR

RUN	Ib (1993-95) (6x6)	Run IIa (36x36)	With RR: Run IIa (140x105)	With RR: Run IIb (140x105)	
Protons/bunch	2.3×10^{11}	2.7×10^{11}	2.7×10^{11}	2.7×10^{11}	
Antiprotons/bunch*	5.5×10^{10}	3.0×10^{10}	4.0×10^{10}	1.0×10^{11}	
Total Antiprotons	3.3×10^{11}	1.1×10^{12}	4.2×10^{12} **0.48E13**	1.1×10^{13}	**1.25E13**
Pbar Production Rate	6.0×10^{10}	1.0×10^{11}	2.1×10^{11}	5.2×10^{11}	hr^{-1}
Proton emittance	23π	20π	20π	20π	mm-mrad
Antiproton emittance	13π	15π	15π	15π	mm-mrad
β^*	35	35	35	35	cm
Energy	900	1000	1000	1000	GeV
Antiproton Bunches	6	36	103	103	
Bunch length (rms)	0.60	0.37	0.37	0.37	m
Crossing Angle	0	0	136	136	μrad
Typical Luminosity	0.16×10^{31}	0.86×10^{32}	2.1×10^{32}	5.2×10^{32}	$cm^{-2}sec^{-1}$
Integrated Luminosity†	3.2	17.3	42	105	pb^{-1}/week
Bunch Spacing	~3500	396	132	132	nsec
Interactions/crossing	2.5	2.3	1.9	4.8	

Required Initial Cooled Beam

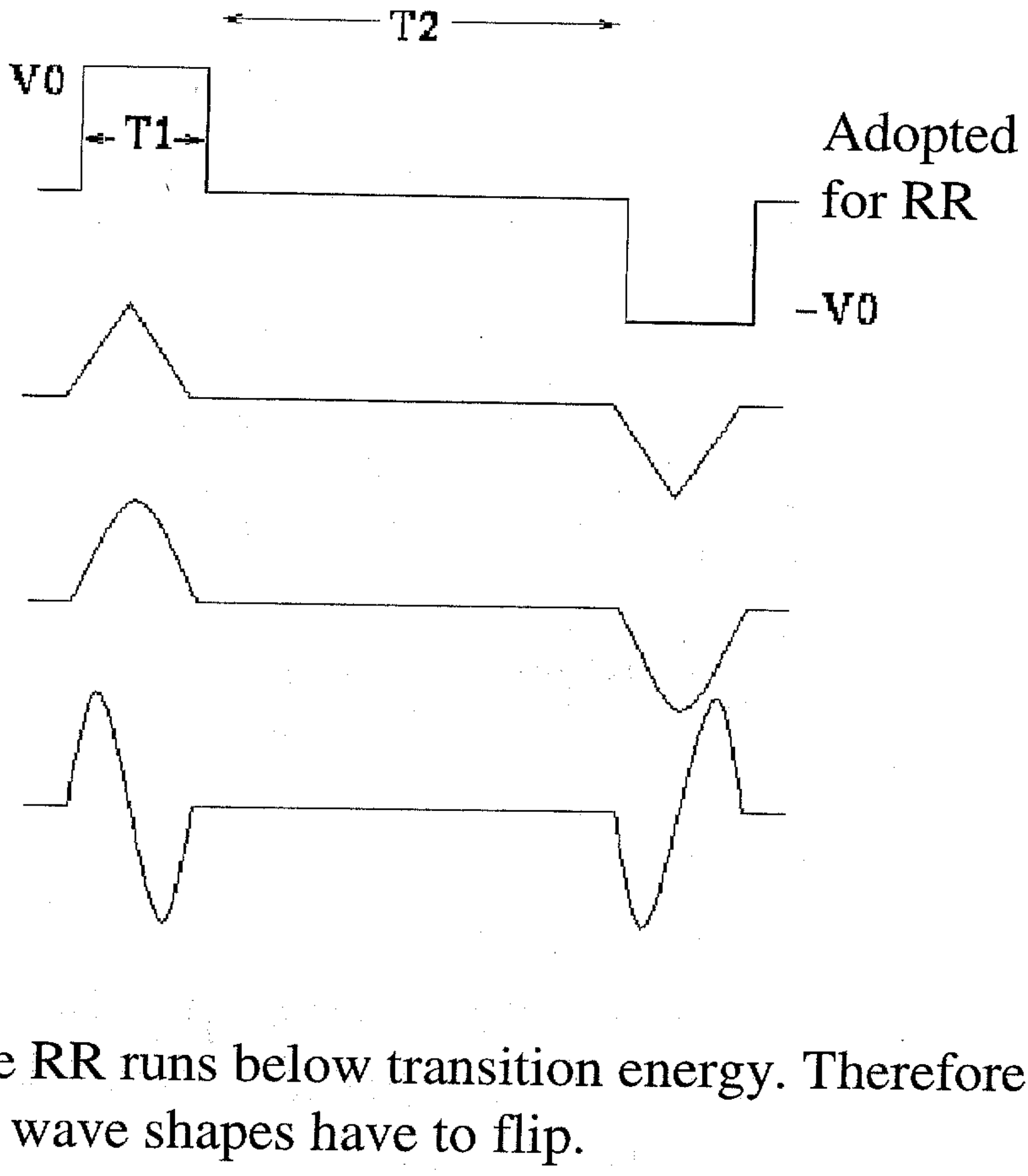
Why do we have to use barrier buckets in RR?

- RR is an 8 GeV pbar storage ring. At any given time, the RR requires to have up to three different regions



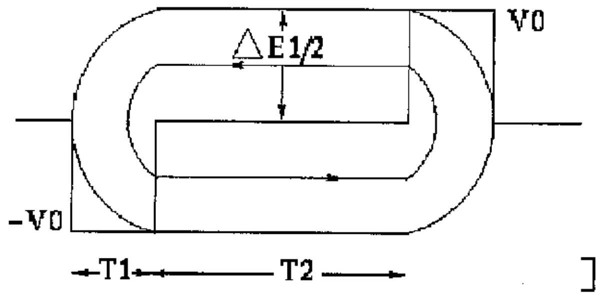
  - Cooled beam ~54 eVs,
  - Hot beam ~108 eVs
  - Transferred beam ~10 –16 eVs
- Each one of them serve specific functions.These specifications demand use of barrier buckets.

Choice of RR Barrier Buckets



The RR runs below transition energy. Therefore the wave shapes have to flip.

Properties of Barrier Bucket



Bucket area :

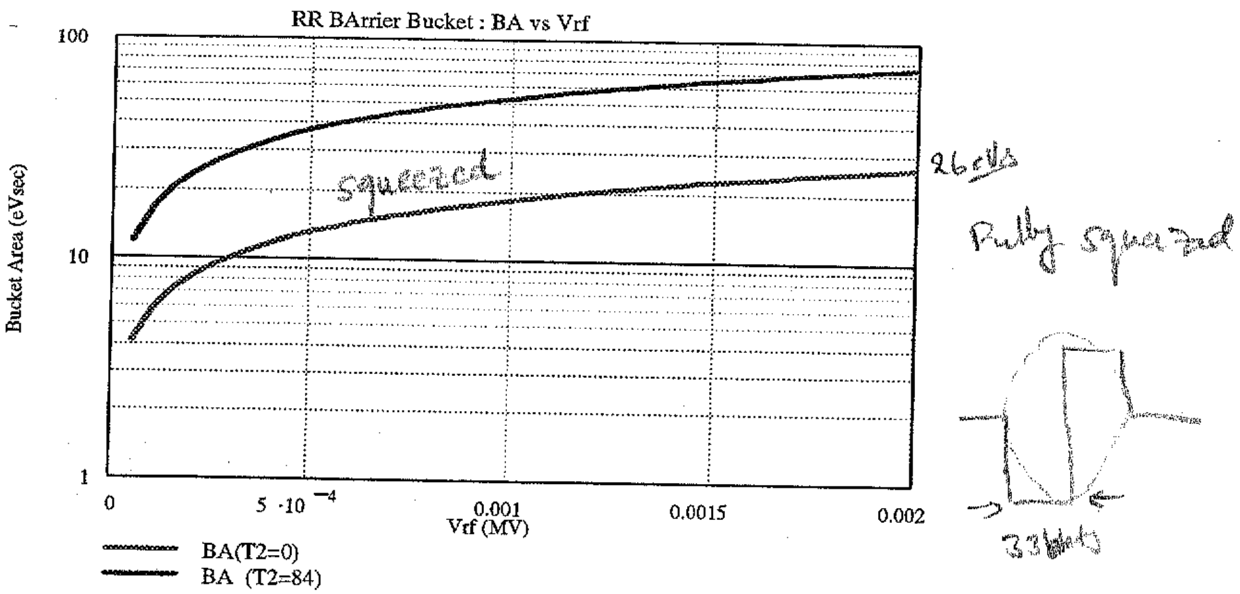
$$\mathcal{A} = 2T_2\Delta\hat{E} + \frac{8\pi|\eta|}{3\omega_0\beta^2 E_0 e V_0}(\Delta\hat{E})^3.$$

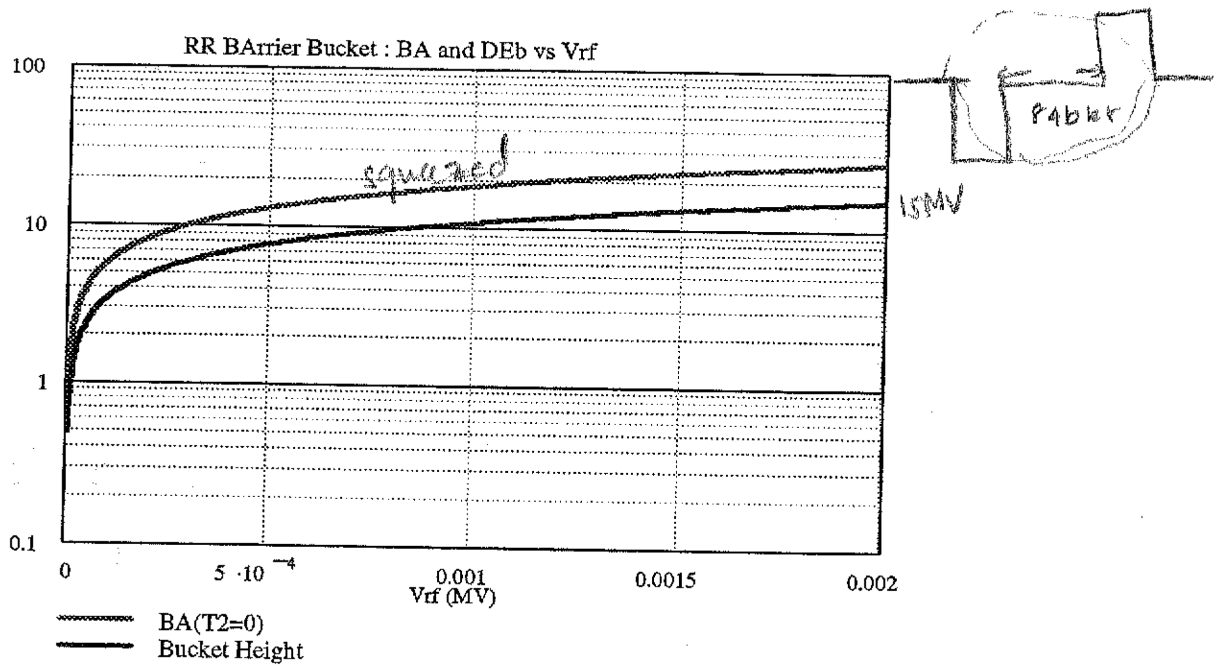
Bucket half height :

$$\Delta E_b = \left(\frac{eV_0 T_1}{T_0}\frac{2\beta^2 E_0}{|\eta|}\right)^{1/2}$$

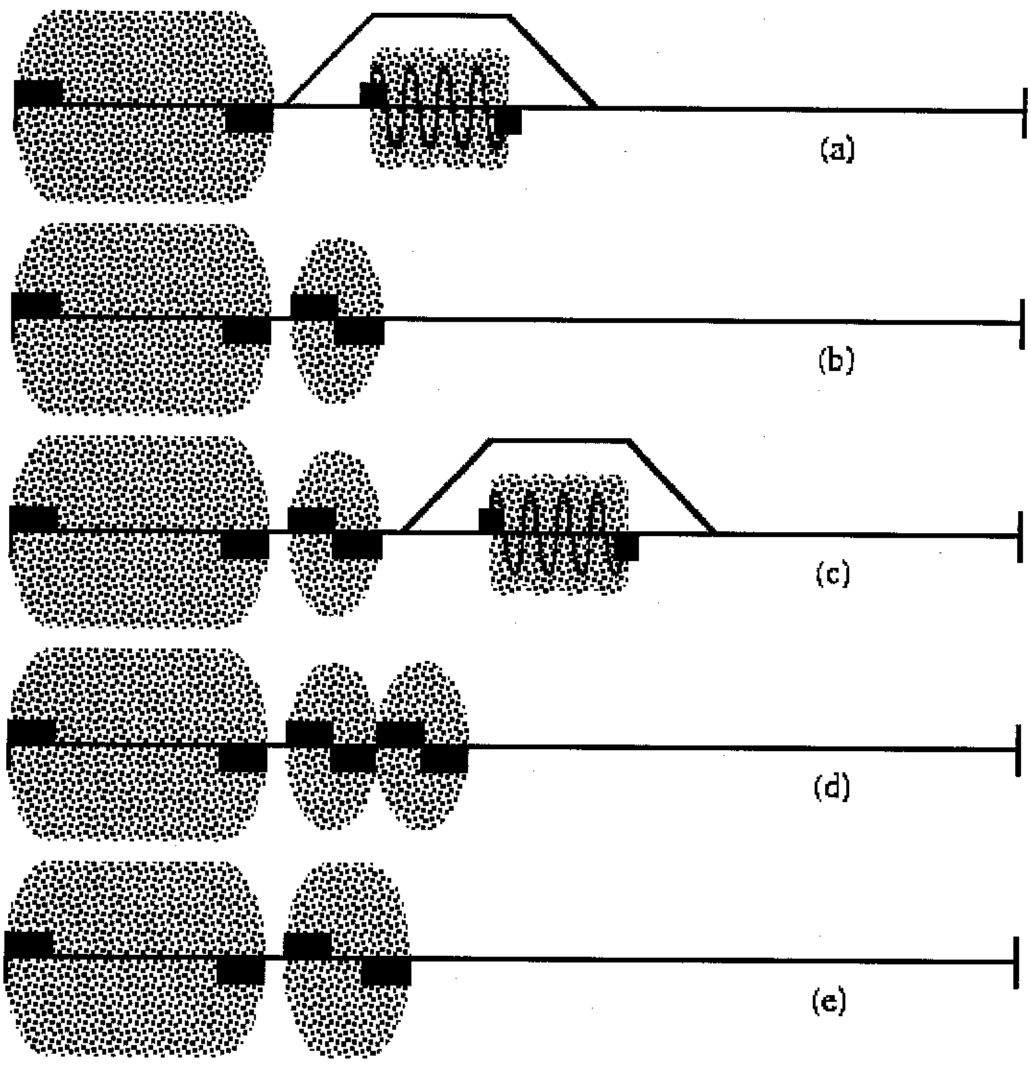
- η is phase slip factor,
- E_o is synchronous energy,
- $\omega_o = 2\pi f_{rev}$ with f_{rev} = beam circulation frequency.

Barrier Bucket



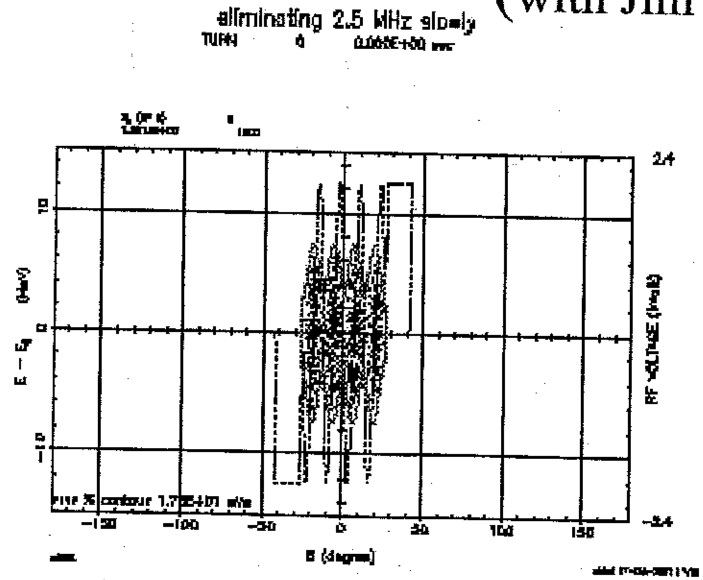


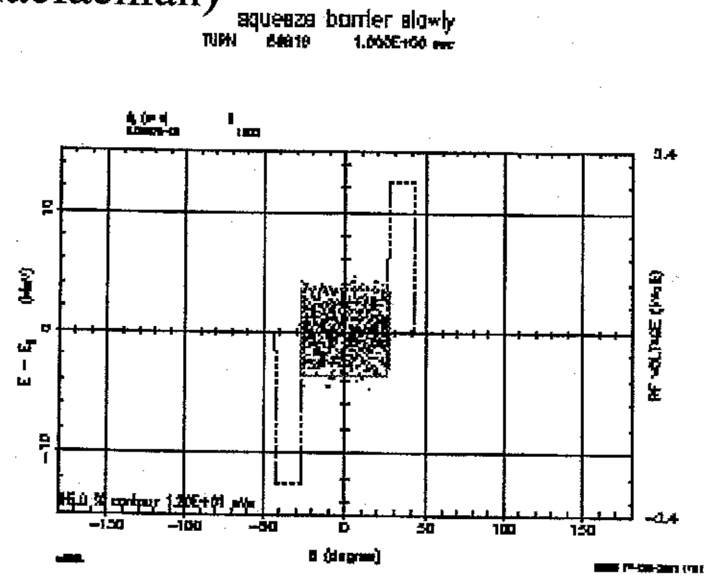
RF Manipulations in RR using Barrier Buckets for Stacking

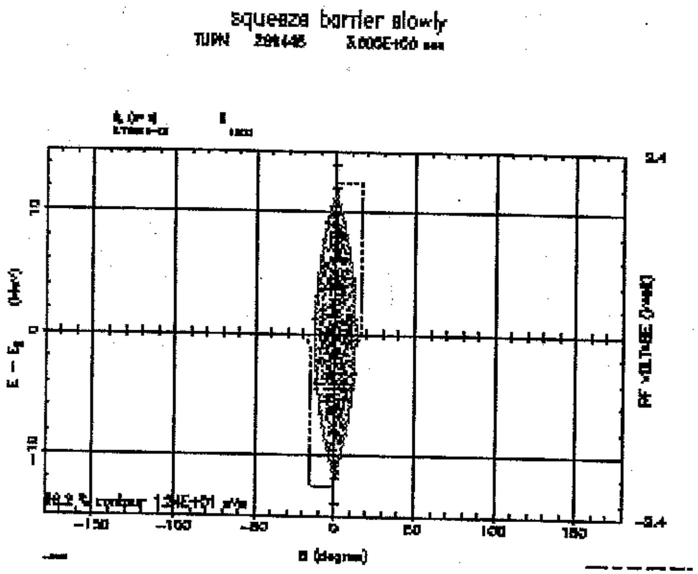


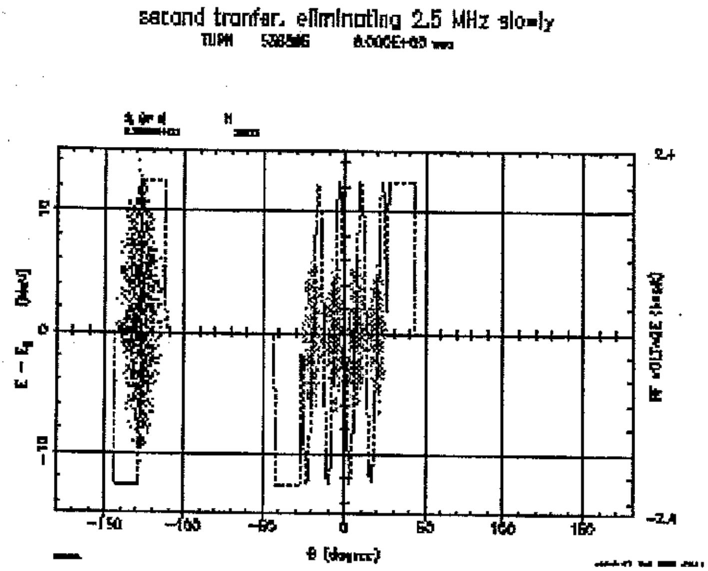
Computer Simulation of Beam Stacking in RR

(with Jim Maclachlan)









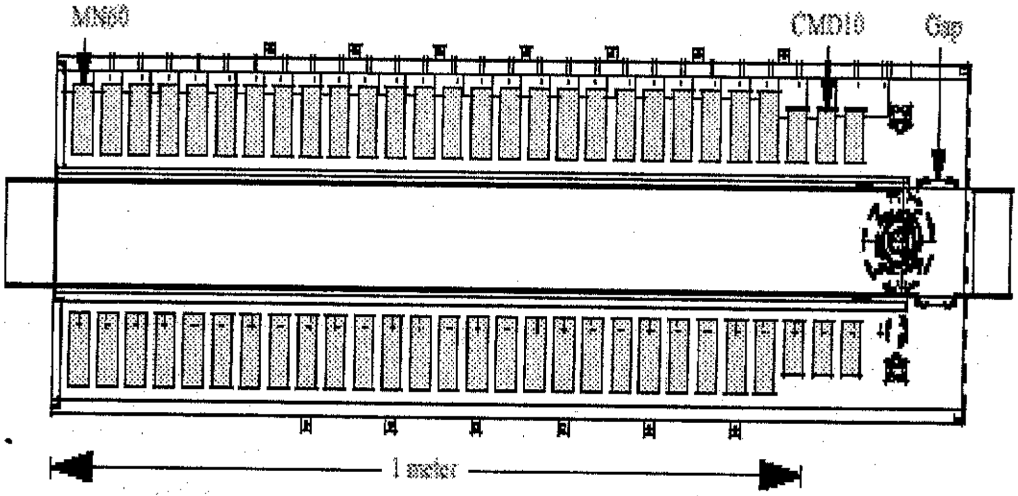
Longitudinal Beam dynamics simulations:
How fast can one squeeze ?

- Initial beam conditions :
  - $E_s = 8$ GeV
  - $\varepsilon_l = 12$ eVs

T(Squeeze)	$\Delta\varepsilon/\varepsilon$
2.0	5%
1.4	5%
0.8	8%
0.6	13%
0.4	21%
0.2	71%

Wideband RF cavity of RR

- This is a broad band RF system operating in the Frequency range of 10kHz to 100MHz

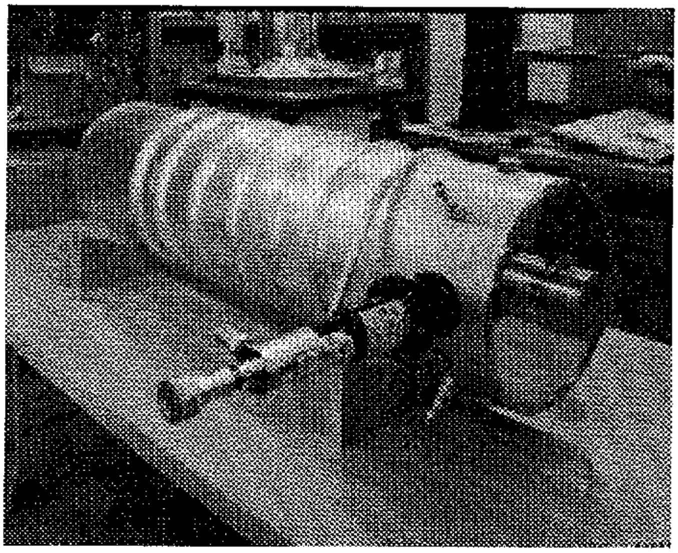


Schematic drawing of Recycler Wideband RF Cavity

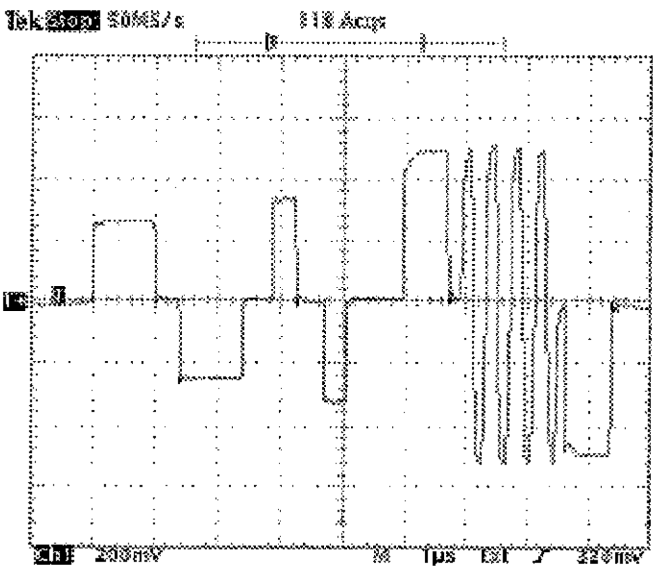
- This consists of four ferrite loaded cavity each driven by 3.5KW solid state amplifier and capable of providing a gap voltage of 500V with total maximum voltage of 2kV.

- **Joe Dey and Dave Wildman PAC99, 869**

Test of RR RF cavity

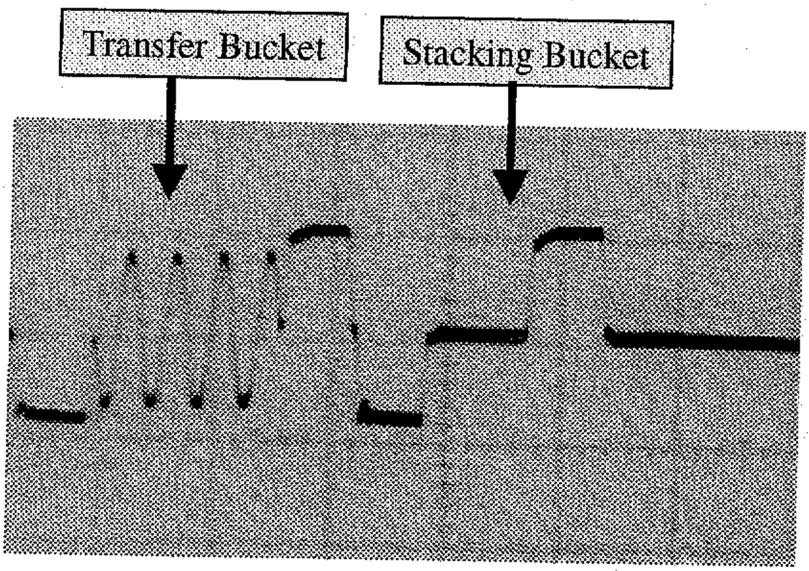


RF cavity on the test stand

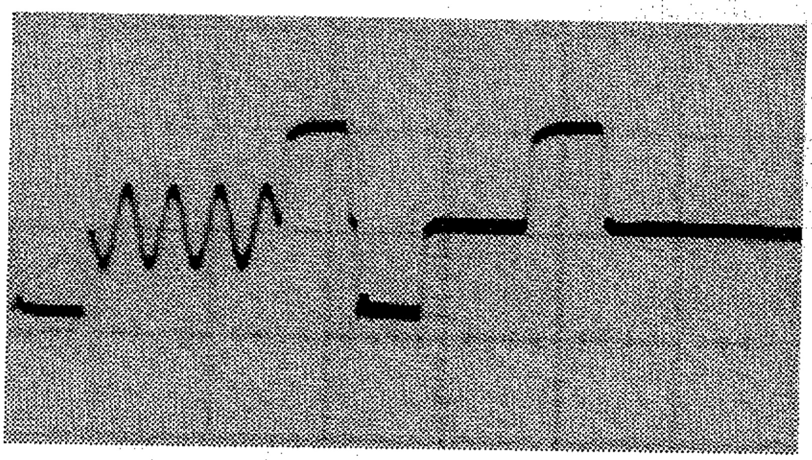


Output signal from one of the four RR RF cavity gap monitor. This data is taken without beam

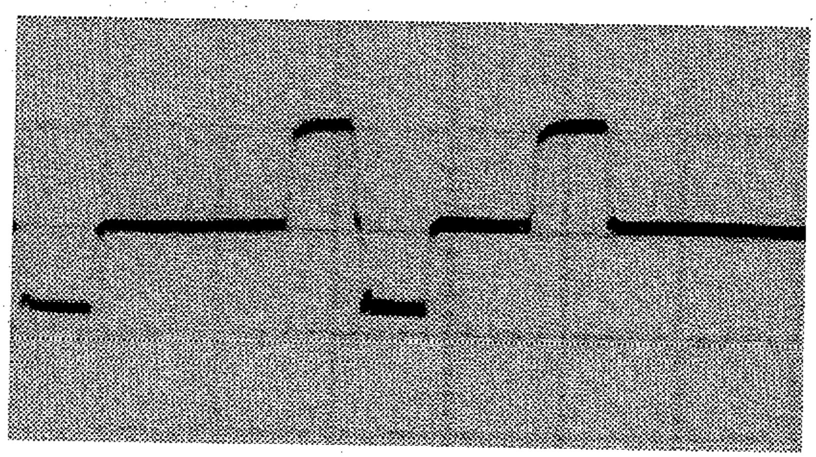
RR: Barrier Bucket Configurations for beam stacking



- 2.5 MHz buckets opened for bucket to bucket transfer from MI to RR

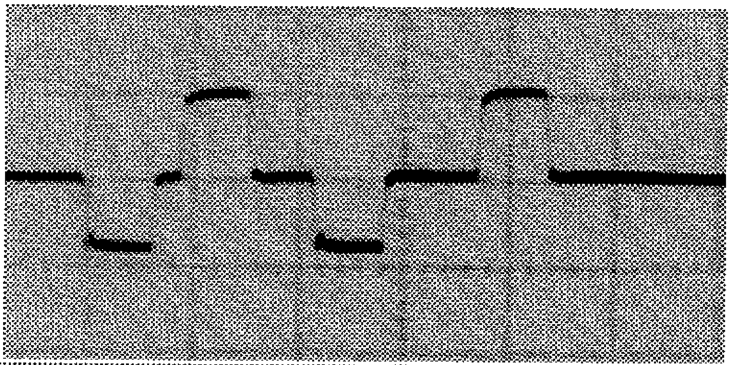


- Adiabatic debunching of 2.5 MHz buckets in RR

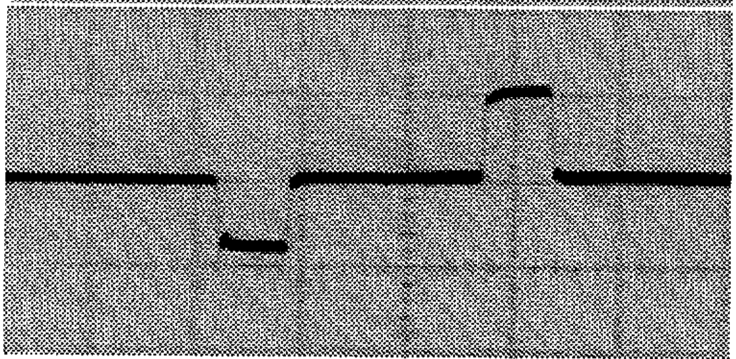


- Completely debunched state

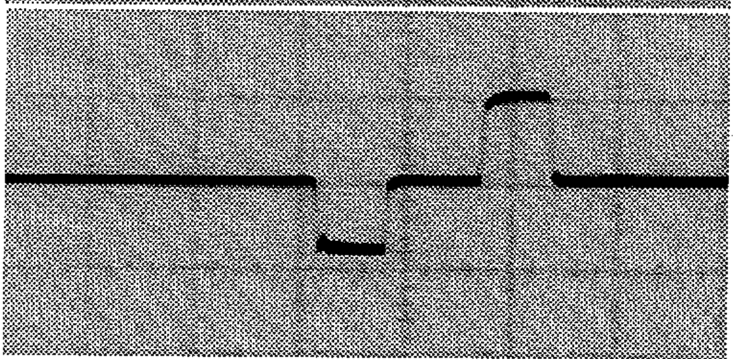
RR: Barrier Bucket Configurations for beam stacking (cont.)



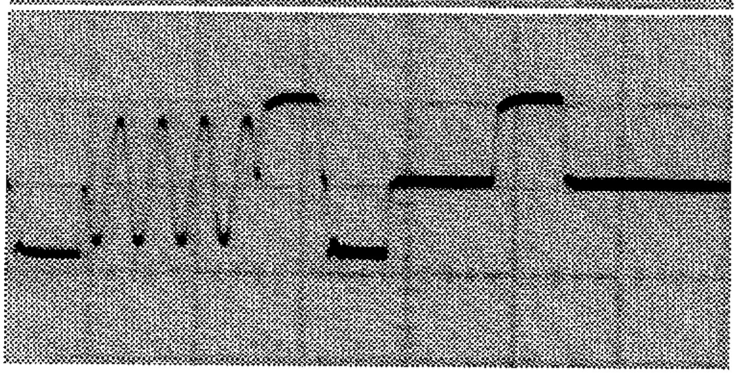
- After squeezing the transfer bucket



- After merging the transfer beam into stacked beam

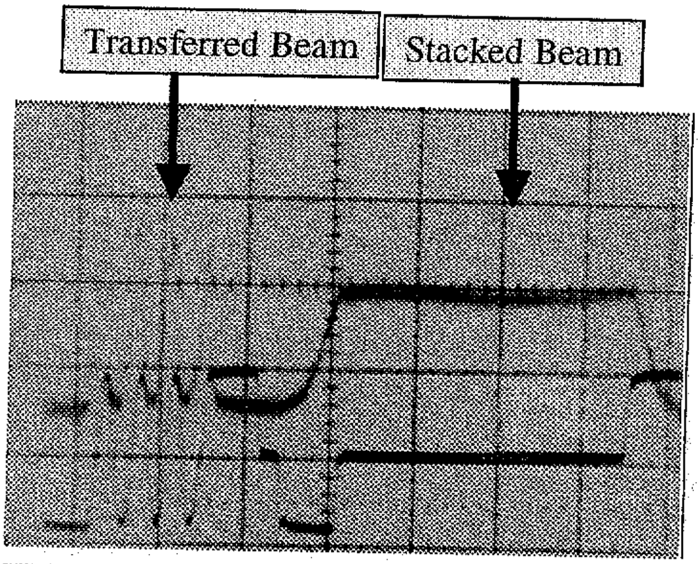


- Before opening the next transfer bucket

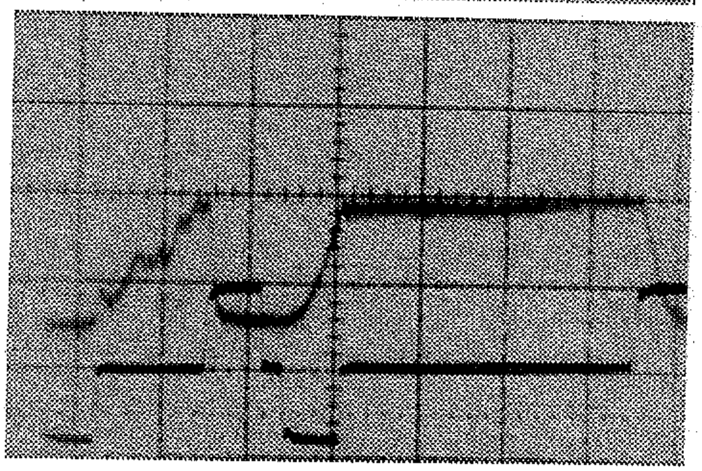


- Ready for next transfer

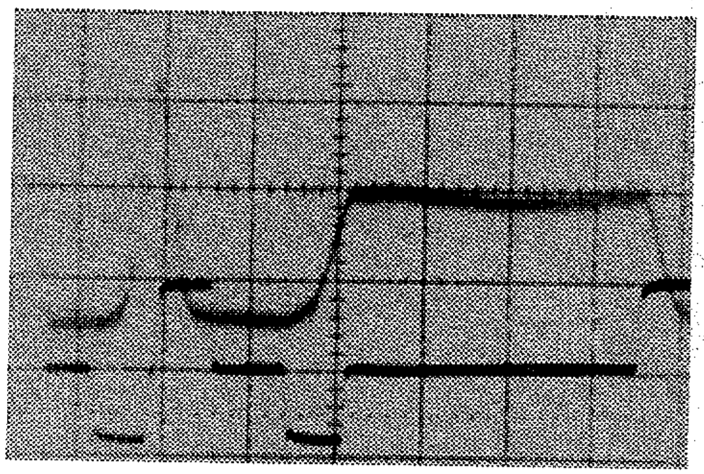
Pbar Stacking in RR



- Beam in the 2.5 MHz buckets and in stacking bucket

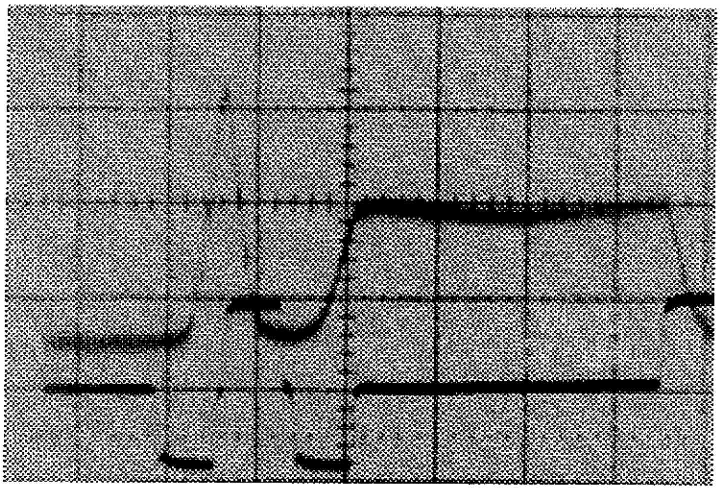


- Debunched beam in stacking bucket

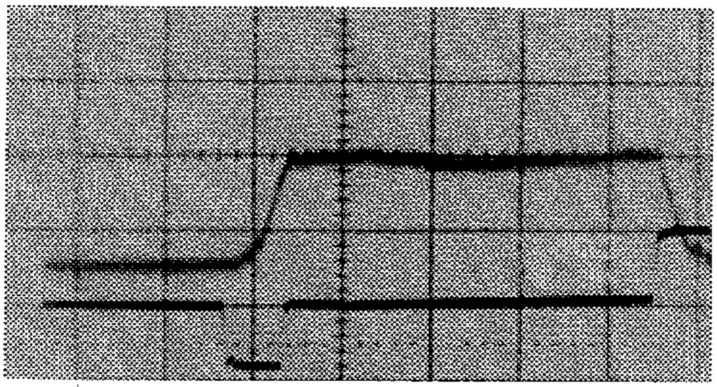


- Squeezed beam in stacking bucket

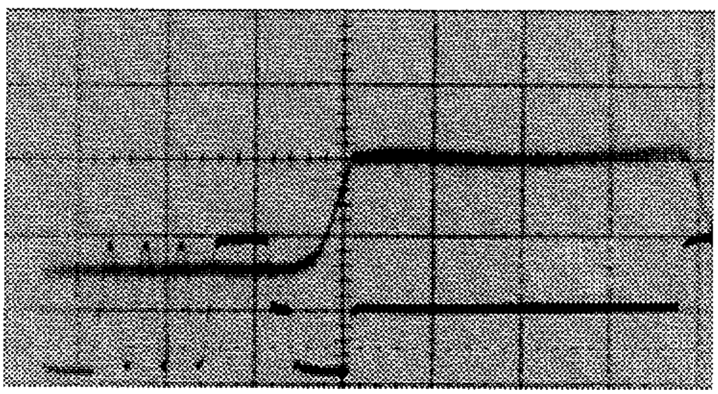
Pbar Stacking in RR (cont.)



- Beam just before merging

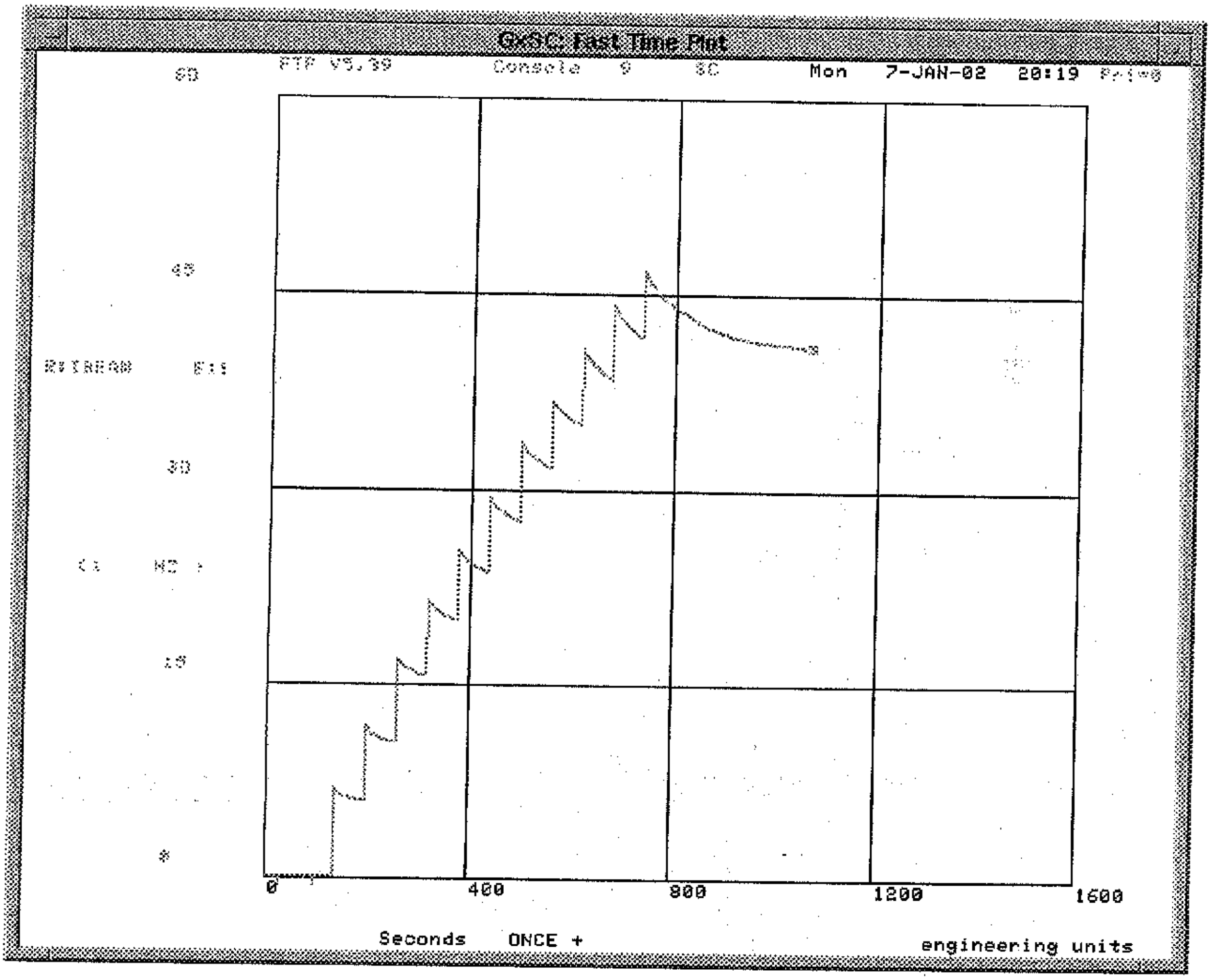


- After merging



- Ready for next transfer

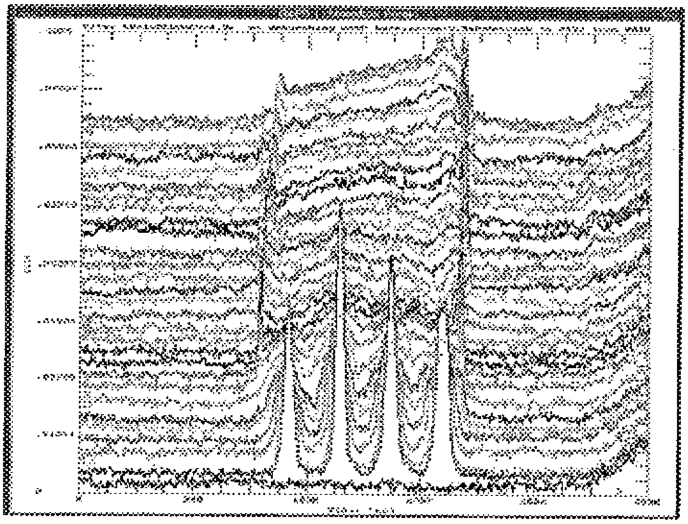
Proton Stacking



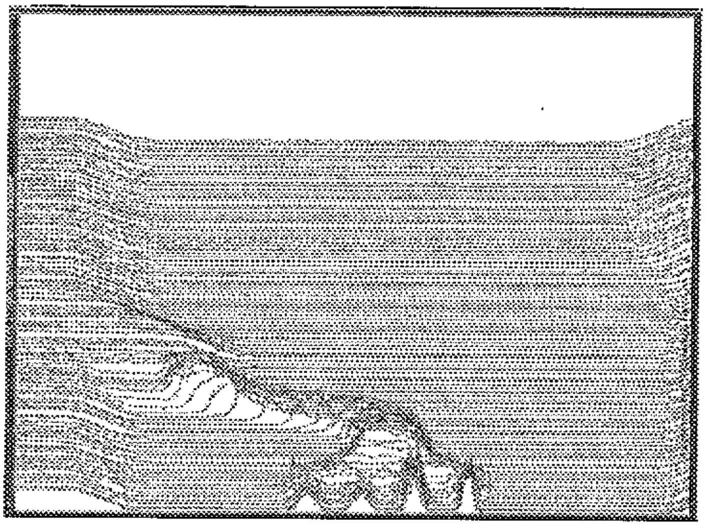
We have demonstrated

- **Stacking of protons ~ 750E10**
- **Stacking of pbars ~ 30E10**
- **Successful extraction of protons from a stack and transfer to the Main Injector**

Beam in Transfer and Stacking Barrier Buckets

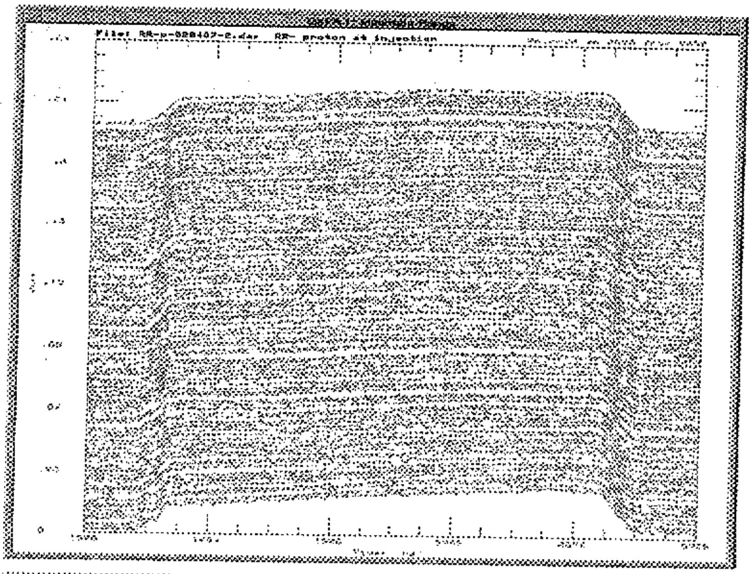


- Injected beam in barrier buckets and debunching

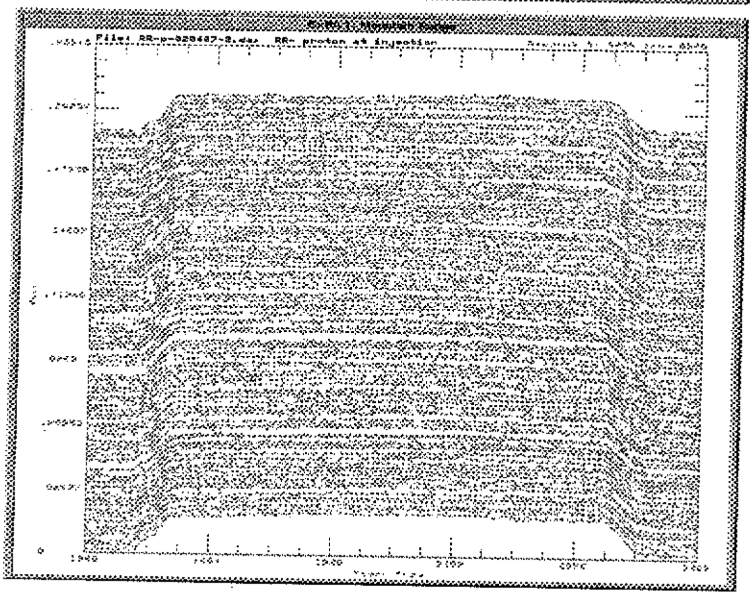


- Injection to stacking

Experiment to eliminate the asymmetry in the beam distribution in RR barrier buckets



- Slanted distribution because of barrier pulse of different area



- Corrected distribution

Conclusions and Plans

- Beam handling in the Fermilab Recycler Ring using barrier buckets will be an integral part of the RR operation.
- We have successfully transferred proton and antiproton beams from MI to RR and back using barrier buckets and have stacked beam in RR barrier buckets.
- Accurate measurement of longitudinal emittance is important to understand the beam dynamics in RR. Some initial efforts have been made.
- Presently we use Schottky detectors to measure the emittance of coasting beam. We plan to extend this technique for beam in barrier buckets by properly gating.
- There are many challenges to be met